Scanning aircraft structures using open-architecture robotic crawlers as platforms with NDE boards and sensors

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ABSTRACT

Rapid inspection of large areas has been an ongoing challenge to the NDE community. The need for such a capability grew significantly in recent years as a result of the increase in the numbers of aging aircraft in service and of aircraft with composite primary structures. While aging aircraft with metallic structures are susceptible to corrosion and cracking mostly near fastener areas, composites are sensitive to impact damage that can appear anywhere on the structure. Field inspection using manual scanning is labor intensive, time consuming and subjected to human error, whereas removal of parts from an aircraft for a lab test is costly and may not be practical. Effective field inspection requires a portable, user friendly system that can rapidly scan large areas of complex structures. In recent years, various portable inspection systems have emerged including scanners that are placed at selected locations and sequentially repositioned to fully cover the desired areas. The development of such systems followed the technology evolution and it requires integration of multidisciplinary expertise including NDE, telerobotics, neural networks, automated control, imbedded computing and materials science. The overall evolution has been towards full automation and there is a desire to have a completely autonomous inspection capability. Recently, JPL developed the multifunction automated crawling system (MACS) offering an open architecture robotic platform for NDE boards and sensors. This crawler established the foundations for the development of a "walking" computer platform with standard plug-in NDE boards. This capability will allow a larger pool of companies and individuals to become potential producers of NDE instruments. Thus, a significant cost reduction can be materialized with a rapid transition of novel concepts to practical use. The capability and potential of MACS as an enabling technology will be discussed in this paper.

INTRODUCTION

The current use of aging aircraft significantly longer than their design life has added a great degree of urgency to the ongoing need for low-cost, rapid, simple-to-operate, reliable and efficient NDE methods of detection and characterization of flaws. The issue of aging aircraft is of concern to the users and operators of both military and commercial aircraft. The 1988 failure of the Boeing aircraft operated by Aloha Airlines heightened the level of attention to the issue of aging commercial aircraft among manufacturers, users and the Federal Aviation Administration (FAA).

Inspection of aircraft in service requires rapid on-site examination rather than removal of parts for a lab test. Manual field inspection is labor-intensive, time consuming, demands great attention to details by the inspectors and it is subject to human errors. The interpretation of the data depends critically on the inspectors' experience, competence, attentiveness and meticulous dedication. For instance, rivet crack inspection using eddy current is known to be a mundane and painstaking task, which can lead to a significant decrease in the inspector attention during a long inspection session. Disassembly of structures and inspection in laboratory conditions offer a greater reliability of the test results, however it is costly and, in many cases, is not a practical approach. The limitations of field inspection are hampering the growth in usage of composite structures for construction of aircraft since they require more often an inspection of large areas. This is due to the fact that composite structures are sensitive to impact damage in service, which can occur at any point and any time. To overcome the limitations of field NDE methods, scanners are being developed to perform automatic and rapid scanning of large and complex-shape structures. For military aircraft, in addition to the desire to increase the speed and reliability of the inspection, there is a need in some applications to operate at harsh, hostile and/or remote conditions (extreme temperature, battlefield, remote expertise, etc.).

Since the introduction of microprocessors, various types of portable scanners were developed using such NDE methods as visual, eddy currents, ultrasonics, shearography, radiography and thermography. While most scanners have been dedicated to a single inspection method, there is an overall trend to combine the capability of more than one inspection method. Increasingly such a multi-mode option is becoming commercially available and systems, such as the MAUS (Boeing, St. Louis, MO), are offering interchangeable components to perform more than one test method [1]. While not applied simultaneously yet, the leading NDE methods that are used in such scanners include mostly eddy current and ultrasonics. Efforts are being made to add also a visual inspection capability.

A recent study by NATIBO (North America Technology and Industry Base Organization), which consists of individuals from the US Department of Defense (DoD) and Canadian Dept. of National Defense (DND), concluded that there is a need for a multi-mode rapid scanning system with an open architecture. This study has added another incentive to the need for effective systems of aircraft inspection in field conditions. Corrosion in aging aircraft was recognized as a serious issue for the military since many aircraft models have been in service for 25-40 years and there is an effort to use them for 40 more years. The cost of corrosion to DoD is estimated at $1B and it needs to be effectively reduced. While it is a costly item, corrosion as a flaw does not lead to aircraft fleet grounding unless it is expected to cause the development of a crack, which in most cases is a slow process. NATIBO's two-year study, entitled Corrosion Detection Technologies Insertion Program Selection, resulted from the recognition of the effect of corrosion on the resources of these departments of defense and on the durability of their existing aircraft systems. Some of the issues are the result of budget reduction, loss of manpower leading to loss of "corporate memory", and restrictions as a result of environmental concerns. It was determined that there is a need for rapid inspection of large areas, accounting for the different corrosion types, increasing the Probability Of Detection (POD), lower cost of operation, reduce aircraft downtime and increase mission readiness. The developed technology needs to leverage commercial capabilities, have multiple applications, be easy to use, operate rapidly and have an open architecture. Following this study, it was concluded that there are three technologies that need to be addressed more closely including a) multi sensors, b) sensor fusion and c) robotic inspection. Three specific methods were recognized as the most effective for corrosion including

a) Edge of light technique, which is a highly sensitive visual technique developed recently by the Canadian National Research Council [2].
b) Eddy Current - This method is widely in use in aircraft inspection and recent studies of pulsed eddy current has been encouraging to consider this emerging approach [3].
c) Ultrasonics - This method is also widely in use for detection of corrosion. To address the need for a couplant, the Iowa State University dripless bubbler was recommended as an effective coupling alternative [4].

The recently developed multifunction automated crawling system (MACS) offered enabling technology for the simultaneous operation of several methods using a single scanner. Such a crawler can travel on an aircraft structure and automatically perform inspection tasks that can be controlled remotely and can be made eventually autonomous. It offers a robotic platform for the integration of a suite of sensors and intelligently scanning and testing aircraft for corrosion and other defects. This paper will review the technology evolution towards using robotic inspection, the recently developed capability, the expected development direction and the role that intelligent NDE can play [1, 5].

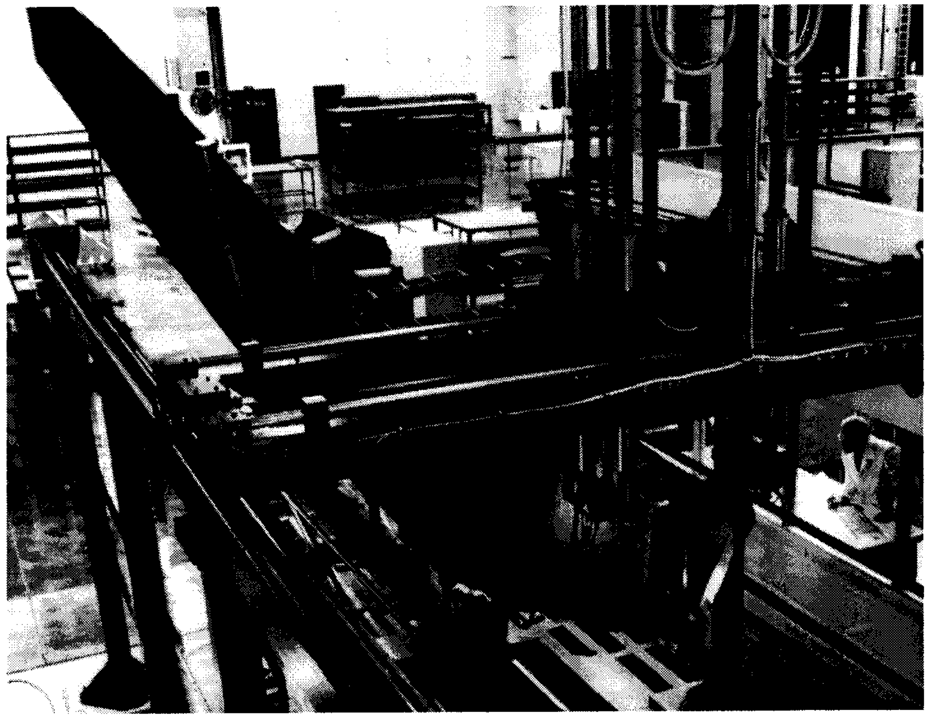
RAPID INSPECTION SCANNERS

Nondestructive evaluation techniques can be distinguished by their ability to provide information about a specific location or a large area in a single test (see Table 1). Radiography, Thermography, Shearography, Magnetic Particles and Liquid Penetrant are providing defect information about an area. On the other hand, sensor base methods that include ultrasonics and eddy-current are requiring scanning in order to provide defect information in a desired area. Otherwise, the data that is obtained is limited to the specific location that is as small as the probe area or less. For a limited area of centimeters in size, transducer arrays were introduced to allow electronic scanning for rapid imaging as in medical ultrasonics, whereas for a larger areas mechanical scanning are used. Over the last four decades, scanners were developed to support ultrasonic inspections to produce B-scan and C-scan images. Generally, the development of scanners made the biggest impact on the wide use of ultrasonics since scanners allowed producing detailed images of the flaws size and location. Moreover, these scanners offered a form of documenting test results, allow consistent data acquisition capability, and offered a simplified acceptance/rejection approach. In recent years, significant progress has been made in the area of eddy-current scanners allowing imaging of eddy current C-scan data. For a long time, the automated inspection capability (also known as C-scan) was available only for lab conditions and field inspection was performed manually. The emergence of microprocessors enabled to make lab systems that are capable of contour-following of structures to overcome the sensitivity of ultrasonic tests to having the beam normal to the surface. Also, systems were to operate in concurrence with detailed CAD drawings. Since the early 80^{th}, automatic C-scan systems have emerged with the capability to inspect full aircraft structures, such as the wing of the Harrier aircraft (see Figure 1).

Table 1: Methods of extracting NDE information from a test structure.

Approach	Test Method or Mechanism
Sensing	• Remote sensors - Eddy current, magnetic, visual, etc. • Attached sensors - Cracking fuse, resistance gauging, strain gage, acoustic emission, ultrasonic, eddy current, fiber optics • Sensitive coating - Bruising paint indicator, brittle coating, liquid crystals • Imbedded sensors - Fiber optics, dielectric, eddy current, magnetic, ultrasonics
Manual operation	• Most widely used methods are visual and tap testing • Inspector operates an NDE instrument at the test site producing the equivalent of A-Scan.
Scanning	• Scanning - Manual and mechanical B- or C-scanning • Imaging/viewing - Visual inspection of large area using CCD • Illumination - Infrared, shearography, reflection/enhancement screen • Beam sweeping - Laser induced ultrasonic scanning • Crawlers - Miniature rover crawling over the structure

Figure 1: A large scanner testing a full wing of an aircraft at Boeing Aircraft, St. Louis, MO.



With the evolution of personal computers and microelectronics, it became possible to produce portable C-scanners that can operate in depot and field conditions [1, 5]. The original portable scanners were relatively heavy and consisted of a simple bridge that can be carried to the field in a mobile set of boxes to perform scanning, data acquisition, imaging and storage. To support the formation of the C-scan images, encoding methods were developed to identify the probe location while operating on aircraft structures. Such position encoding methods included the use of acoustic waves, as in the ISIS system that was developed in the early 80th by General Dynamics under an Air Force contract (see Figure 2), optical scales and other encoding techniques. Due to the inaccuracy of the acoustic encoding technique it was phased out and most of the current portable scanners rely on optical encoders. To inspect vertical surfaces and upside down surfaces of aircraft wings, strapping techniques (see Figure 3) and vacuum cups are used to attach the portable C-scan bridge to the test area. An example of a portable scanner that uses vacuum cups to secure its attachment to the test structure is shown in Figure 4.

The introduction of portable c-scan bridges enabled to semi-automate the ultrasonic field inspection and to significantly improve the reliability of such field tests. Since aircraft structures have a complex geometry, the use of a flat rigid C-scan bridge is facing difficulties associated with the gap between the flat surface of the bridge and the curved surface of the aircraft. The PANDA Scanner (made by Tektrend, Quebec, Canada) followed by MAUS (Boeing, St. Louis, CA) and others addressed this issue by employing a flexible arm. Being a contact-scanning device, the PANDA's spring-loaded transducer holder has the flexibility to follow the contour of an aircraft structure. The PANDA bridge with the flex arm is shown in Figure 5. The arm can be flexed to adapt the bridge curvature to the surface contour of the aircraft and thus ensuring the transducer contact to test surface during scanning.

Figure 2: C-scan bridge strapping firmly attaches the scanner to the test object allowing automatic field inspection. (AEA Technology Energy, UK).

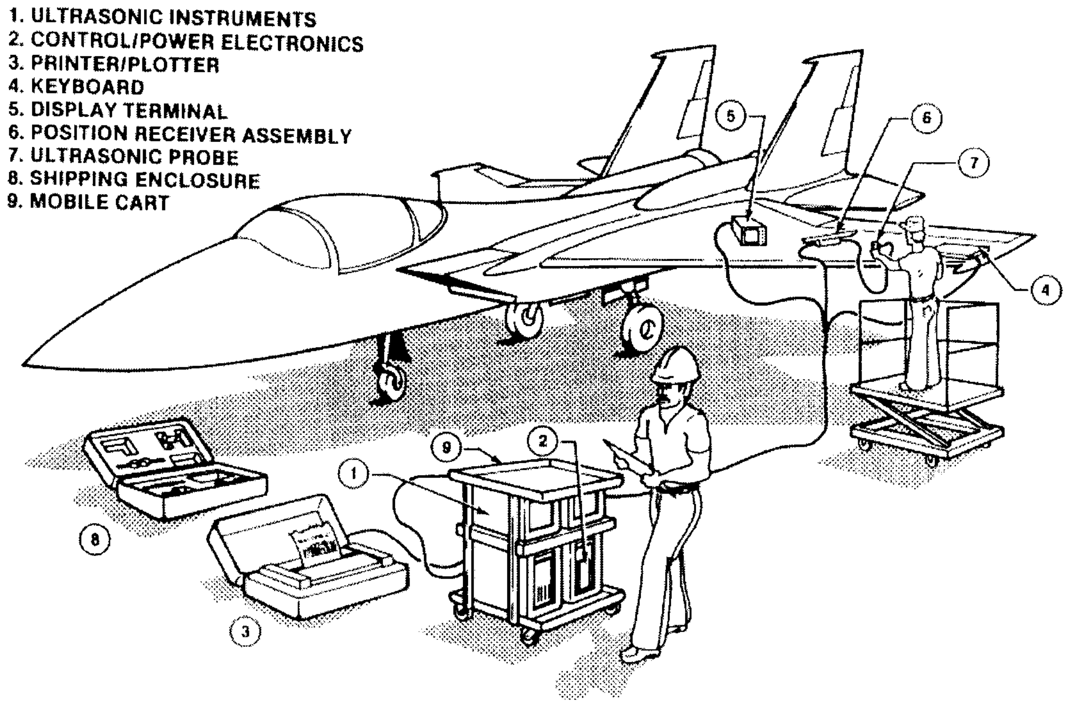


Figure 3: The In-Service Inspection System (ISIS), one of the early generations of the portable C-scanner for field operation.

Figure 4: A scanner using a portable bridge and two suction cups to secure the bridge position during scan (made by QMI, Costa Mesa, CA).

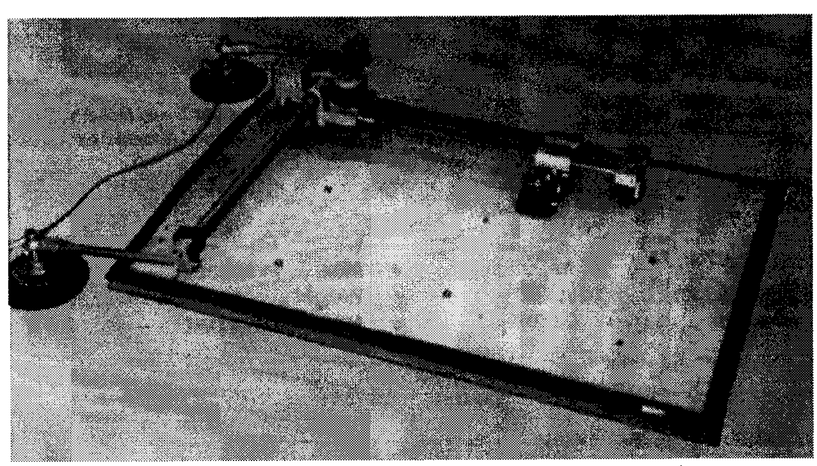
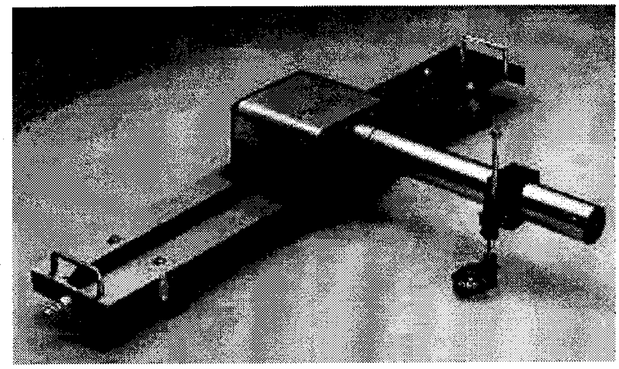
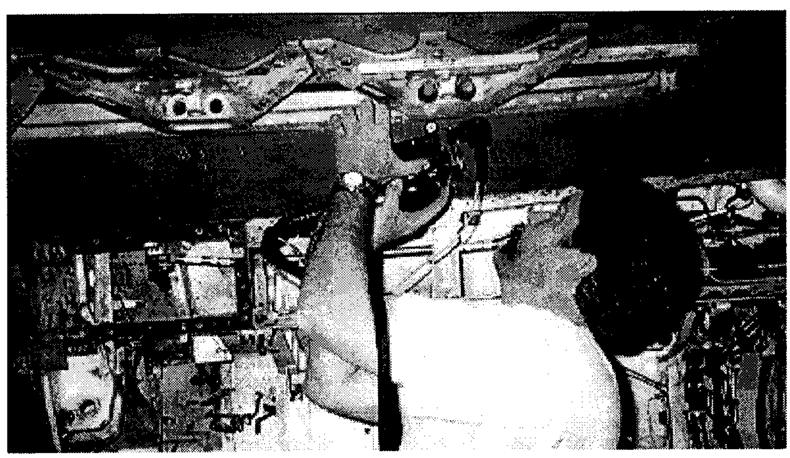


Figure 5: A view of the Portable Automated NDT Arm (PANDA, made by Tektrend, Canada)



Considering the limitation of stationary scanners, the McDonnell Douglas Corp. (prior to being acquired by Boeing) developed at the end of the 1980's a scanner called MAUS that allows semi-mobile scanning. MAUS uses a hand-held scanner that translates a series of probes sideways while an operator is responsible for moving the scanner head forward and backward. Recent modification of the MAUS, the PANDA and other scanner enabled the alternate use of either an ultrasonics or eddy current head. A photographic view of the MAUS in use by an operator is shown in Figure 6. Unfortunately, the need to manually position the scanner head can be a tiring task when inspecting vertical or upside down surfaces. To address this constraint, the MAUS probe mount was modified to an attached bridge that uses suction cups and sequentially moved to cover the desired test area.

Figure 6: A view of the application of MAUS and the hand-held probe in a field test.



Generally, current scanners cover limited area in a single scanning session that is defined by the scanner-bridge dimensions. Covering a large area of an aircraft requires multiple scans where the operator moves the scanner bridge from one location to another in the form of scan-tiles as the full structure is being covered. The use of semi-mobile scanning in the MAUS has been the first step in the direction of full mobility.

INSPECTION CRAWLERS

Scanning an aircraft using a portable bridge configuration has been an effective step in addressing the need for automatic field testing capability. However, the constrain to covering an area only within the bounds of the scanner bridge has limited the operation speed, the accessibility to complex areas (particularly near joint with a wing, etc.) and required scaffolding to allow sequential attachment of the bridge to different locations. Mobile scanners can greatly increase the rate of inspection, minimize human errors and offer flexibility of reaching various areas of the aircraft. These scanners need to have a controlled adherence capability to maintain attachment to the structure surface while traveling and inspecting it. Such scanners, in the form of crawlers, are increasing emerging as a solution to the need for unconstrained mobility and dexterity while conducting automatic scanning. The use of suction cups has become a leading form of controlled adherence to aircraft surfaces and several successful scanners have developed in the last several years. The Automated Non Destructive Inspector (ANDI) and the Autocrawler are some of the more known mobile scanners [1, 5-7]. In recognition of the need to have a compact, more maneuverable crawler, JPL recently developed a small, highly dexterous crawler so-called Multifunction Automated Crawling System (MACS). This crawler, which is shown in Figure 7, was designed to perform complex scanning tasks [8-9] taking advantage of its ability to easily turn or move forward and backward while being attached to a curved surface. A schematic view of MACS traveling and rotating while activating its legs and suction cups is shown in Figure 8 and from different angle views are shown in Figure 9. MACS employs ultrasonic motors for mobility and suction cups for surface adherence. It has two legs for linear motion, with one leg serving as the rotation element for turning. This mobility configuration allows performing any simultaneous combination of motion, including linear travel as well as rotation around the central axis. MACS can be applied to inspecting composite and metallic structures for detection of cracks, corrosion, impact damage, unbonds, delaminations, fire damage, porosity and other flaws, as well as paint thickness measurement. Also, this crawler can be designed to identify dents and individual fasteners.

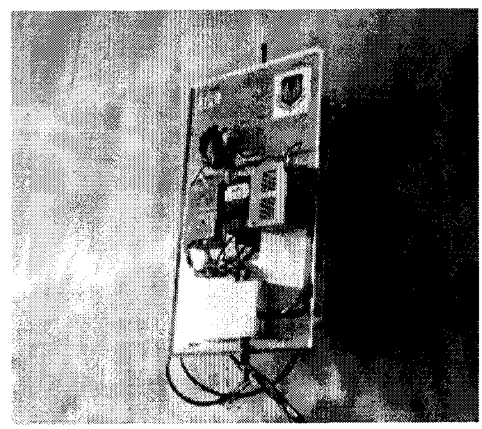


Figure 7: MACS crawling on the C-5 aircraft [8-9].

The development of MACS was benefited from the ongoing JPL development of miniature planetary rovers, as demonstrated by the Mars Pathfinder Mission, as well as telerobotic and NDE techniques. MACS was developed to serve as a generic robotic platform that can be used for many applications, including inspection, paint removal and painting of ships as well as testing/maintaining aircraft. Having many users is expected to lead to lower cost systems that will be improved by a large pool of users and developers. The monitoring of MACS activities can be designed for local control or control via the Internet with password access. A standard PC architecture will enable rapid implementation of new sensors, which can be easily integrated into the setup. To define the crawler functions, plug-and-ply boards will need to be developed and thus enable a new NDE industry that can rapidly introduce novel products as well as transfer technology to commercial use. The JPL's telerobotic program and extensive planetary exploration experience with rover technology are providing a valuable resource to this emerging and enabling technology.

The ability to crawl on surfaces has been enabled by use of suction cup elements that are extended at the stage of attachment. An air pressure in the range of 80 to 120-psi, as can be obtained from conventional pressure lines, is used to eject the suction cups onto the test surface at the moment that the specific leg is made to adhere to the surface. Individual venturi pumps provide each suction cup with sufficient vacuum to assure effective attachment. The ability to adjust the ejection distance of the individual rods allows the crawler to travel on curved surfaces as shown in Figure 10. The smallest diameter of the curved surface, which can be inspected by MACS, depends on the suction cups total ejection length and the size of the crawler platform.

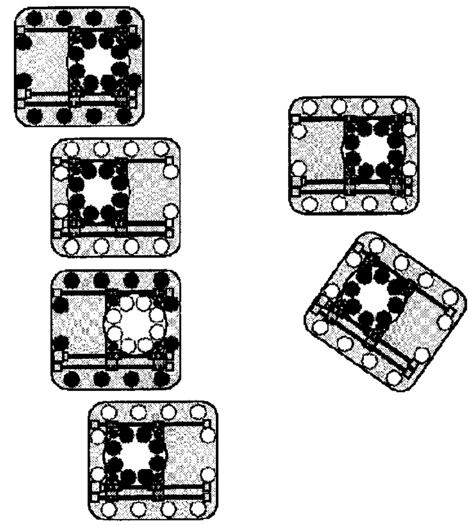


Figure 8: MACS crawler mobility control. Solid circles represent activated suction cups and hollow circles represent resting cups. Forward travel is shown on the left and a simultaneous travel/rotation is shown on the right.

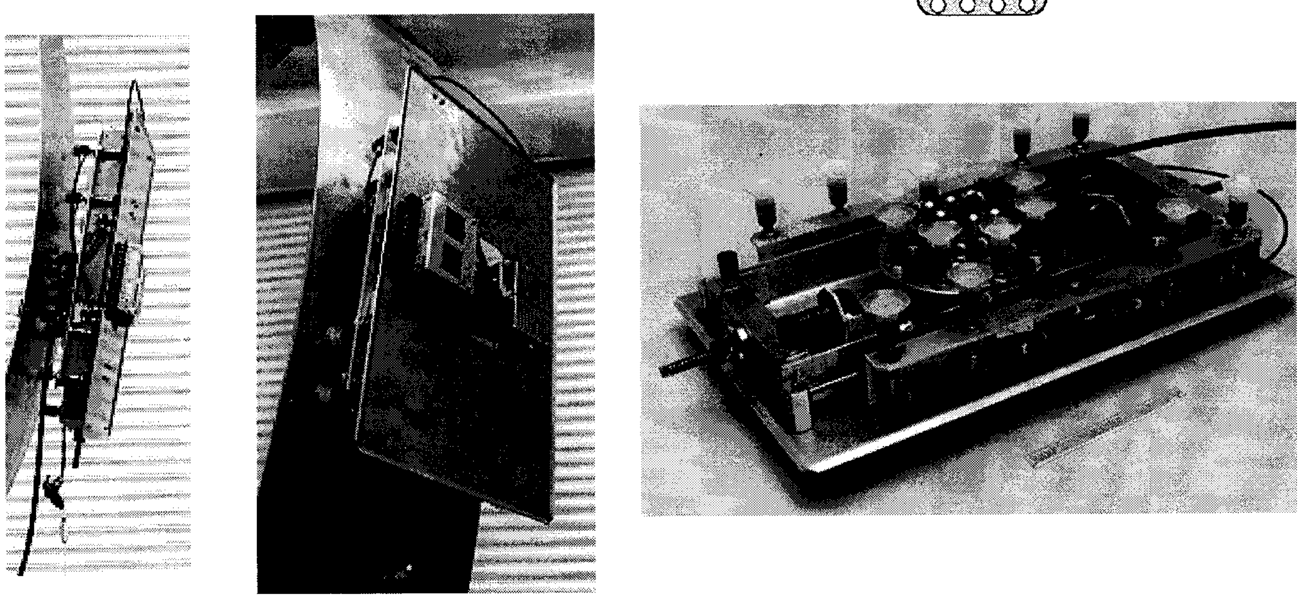
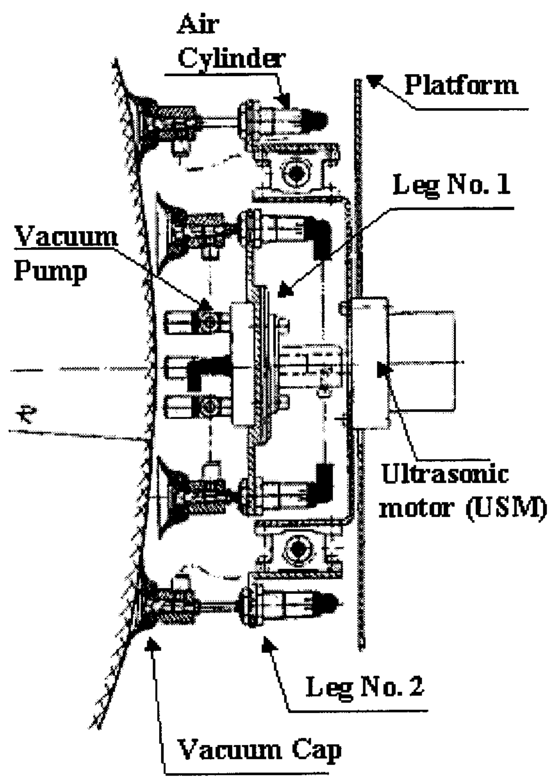


Figure 9: A photographic view of MACS from difference angles, where the two legs and the crawler ability to be attached to a curved surface are shown.

AUTONOMOUS CRAWLERS USING INTELLIGENT NDE

Autonomous operation of NDE crawlers can make a significant impact on the future of field inspection of complex structures, such as aircraft. An autonomous crawler can be monitored remotely by centrally located experts that are equipped with know-how, database, analytical tools, CAD drawing, and accept/reject criteria. Such a capability will allow rapid response to inspection needs, particularly in cases of crisis where it is necessary to examine a full flight of a particular aircraft model worldwide. An autonomous crawler can be operated during aircraft idle time, including night shift, allowing to reduce the need to remove an aircraft from service for inspection. Sensors that are based on visual, eddy current and ultrasonic NDE methods are expected to serve as key inspection tools on future autonomous crawlers. Autonomous robotic technology is currently being studies in numerous areas and at JPL it is being considered for planetary exploration, where the Mars Pathfinder already enjoyed some of its benefits. Miniature robotic technologies with on-board intelligence are being developed for future missions allowing a rover to examine, select and collect planetary samples while avoiding obstacles during operation in an unknown terrain. Since communication between Earth and various planets takes several minutes or more each way, the need for autonomous operation rather than a direct remote control is critical to the success of such NASA missions. The JPL's crawler MACS is currently using umbilical cord for power, communication/control and to provide air pressure for the ejection and activation of the vacuum suction cups. Follow-on efforts are expected to minimize the content of the cord to a safety cable, power and communication. Potential future development will reduce the content further to the level of only safety cable with a miniature on-board pressure pump, power, wireless communication, and computing capability. Progress in the field of miniature electro mechanical system (MEMS) is expected to greatly benefit the inspection crawler technology.

Figure 10: Cross section view of MACS is illustrating its capability to crawl on curved surfaces.



Crawlers can employ local Global Positioning Systems (GPS) and laser localization to determine the absolute coordinates. Further, such GPS systems allow relating the location of the crawler on the aircraft to the detailed drawing and thus assist in the data interpretation for the determination of the acceptability or rejection of flaws as well as the necessary corrective action. To protect aircraft elements that rise above the surface from accidental damage, a vision system can be used in conjunction with collision avoidance software. Data fusion and neural network interpretation can be used to perform intelligent signal acquisition as well as flaw detection and characterization [10].

PLATFORM FOR MINIATURE NDE INSTRUMENTS

The personal computer (PC) technology offers a model for smart mobile platforms, namely the establishment of the equivalent to the motherboard. Various companies are making boards and components for PC allowing them to concentrate on their strength and innovation, rather than having to produce a complete new system each time they launch a new product. As an example, manufacturers of an internet card or a modem can concentrate on improving their product or introduce a new board without having to make a complete personal computer. The key issue is that these companies can dedicate their capability to well defined product area and it is possible due to the motherboard architecture standard to which they maintain compliance.

Crawlers can be developed as "walking computer", i.e. mobile platform, which can use a motherboard to which boards can be added to provide NDE, control, power, intelligence and communication capabilities. The crawlers can be produced by telerobotic companies, which will have standard bus architecture offering a plug-in capability for miniature NDE instruments. Such crawlers will allow the NDE industry to concentrate on making unique miniature instruments modules for plug-in onto the crawlers and making driver software for microprocessor control of the modules. This field is multidisciplinary and just as in the case of the PC technology it is very difficult for a single company to poses all the necessary expertise. This approach offers a larger pool of companies to contribute to the field as well as the ability to standardize the products for a larger user base and thus significantly reduce cost. The engineering side of the crawler technology involves the development of the platform components including the power supply, mainframe, bus and wireless communication, position tracking (local GPS, encoders, etc.), controlled attachment, actuators and motion control. In the area of NDE instruments miniaturization, the field is starting to see some progress but there is much work that needs to be done and more companies need to be involved. The JPL's MACS crawler can serve as a baseline technology for an industry standard. The micro-electronic mechanical systems (MEMS) technology will enable future generations of extremely small scanning NDE instrumentation.

The field is still relatively and more development is needed before an autonomous crawler can become available for robotic inspection of aircraft structures [1]. To accelerate the development, the principal author of this paper has taken an initiative with ASNT to have Sessions on Robotics Miniaturized NDT Instruments in each of the ASNT conferences since the '96 Fall Conference, which was held at Seattle, WA. Efforts are being made to nurture the growth of the pool of companies to are producing miniature instruments and modular plug-ins.

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